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Spatially resolved low-temperature scanning tunneling spectroscopy on AuFe spin-glass films

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Recently, finite-size effects in the electrical transport properties of dilute magnetic alloys have attracted a lot of attention [1]. For very dilute Kondo alloys (concentration c $\sim$ 100 ppm) the spins of the conduction electrons tend to screen the spin of the magnetic impurities, inducing a non-magnetic state below the Kondo temperature T_K. Intuitively, one expects that the Kondo scattering of the conduction electrons is strongly affected as soon as the sample size becomes of the order of the Kondo screening cloud. For a typical Kondo alloy such as AuFe with $T_K \approx 1$ K, the size of the Kondo screening cloud should be a few micrometer, implying that finite-size effects can be conveniently studied in thin AuFe films which have been patterned using electron beam lithography. Some experiments have indeed revealed a pronounced depression of the logarithmic increase of the resistivity at low temperatures when decreasing the sample thickness or width below 1 μm. Another experiment, involving our laboratory in Leuven, failed to observe any size effect down to 40 nm. Experiments on nanometer size point contacts indicated a strong increase of the Kondo temperature when reducing the contact size below 10 nm [2]. Theoretical calculations predict that the size effects may be closely related to the anisotropy of the local magnetic moments which is induced by the sample boundaries in the presence of spin-orbit scattering [3]. Theory also indicates that the amplitude of the size effects is affected by disorder [4] as well as by surface roughness [5].

Size effects have also been investigated in more concentrated (c $\sim$ 1 at.%) spin-glass alloys [6, 7], where at lower temperatures the logarithmic increase of the resistivity caused by the Kondo effect becomes dominated by a resistivity decrease due to the spin-glass freezing process. Size effects, which can be strongly affected by uncontrolled changes in the disorder [7], appear for sample sizes below 100 nm. These effects may be related to variations in the RKKY interaction strength as well as to a transition towards a lower dimensionality for the freezing process.

In this contribution, we will demonstrate the possibility to study size effects in thin films of AuFe spin-glass alloys by investigating the differential conductance near the Fermi level with low-temperature scanning tunneling spectroscopy (STS). As confirmed by point contact experiments, the voltage dependence of the differential conductance can be directly linked to the temperature dependence of the resistivity [8]. The STS measurements provide the unique possibility to probe possible spatial variations of the size effects. Moreover, combining the STS measurements with topographic scanning tunneling microscopy (STM) images of the surface may allow to check the influence of the local surface roughness on the spin scattering processes.

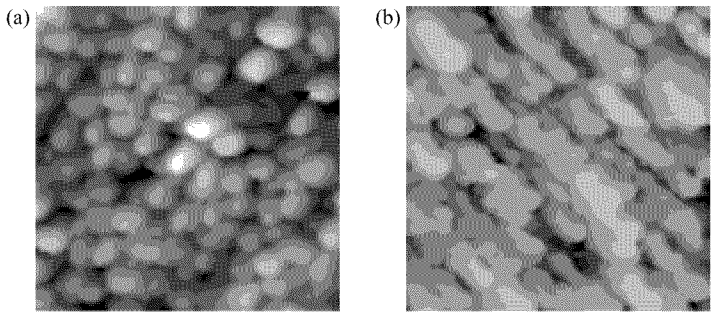

Fig 1. (a) STM image obtained at 300 K of a pure Au film with a thickness of 30 nm. The scanned area is 148 nm × 148 nm and the greyscale corresponds to height variations of 16 nm. The tunnel current has been fixed at 200 pA, and the sample bias at 200 mV. (b) STM image obtained at 300 K of a AuFe film with a thickness of 23 nm and an Fe concentration of 2.65 at.%. The scanned area is 144 nm × 144 nm and the greyscale corresponds to height variations of 17 nm. The tunnel current is fixed at 500 pA, and the sample bias at 50 mV.

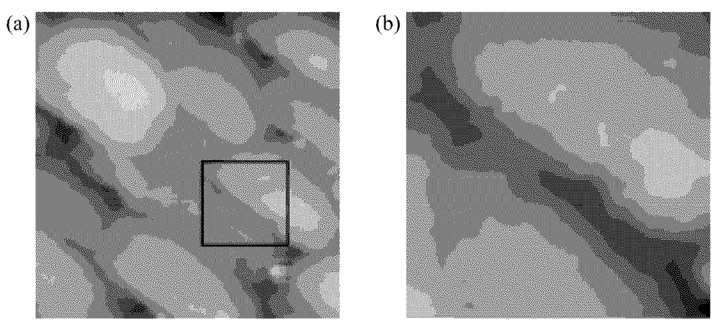

Fig 2. (a) STM image of the AuFe film measured at 5 K. The scanned area is 82 nm × 82 nm and the greyscale corresponds to height variations of 10 nm. The size of the square is 20 nm × 20 nm. The tunnel current is fixed at 10 pA, and the sample bias at 10 mV. (b) STM image of the region inside the black square marked in Fig. 2a.

Our experimental results, which are discussed in this contribution, have been obtained for a thin AuFe film with a thickness of 23 nm and an Fe concentration of 2.65 at.%. The film is produced by co-evaporation onto an oxidized silicon substrate. Topographic STM images of the AuFe thin film obtained at room temperature clearly reflect the polycrystalline film structure with a grain size of the order of the film thickness. The grains composing the film obviously have a different shape and size distribution when compared to the structure of a pure Au film with a comparable thickness of 30 nm and deposited onto an oxidized silicon substrate (see Fig. 1a and Fig. 1b). On the other hand, the root mean square roughness of both films turns out to be the same (2.4 nm). Additional STM experiments for different Fe concentrations will be needed to obtain a better understanding of the influence of Fe impurities on the film morphology.

We have also performed measurements of the AuFe film surface at 5 K with a low-temperature tunneling microscope. The details of our home-built microscope have been described elsewhere [9]. Fig. 2 shows STM topographical images at two different magnifications of the AuFe film surface. We have measured in detail the $I(V)$ char-

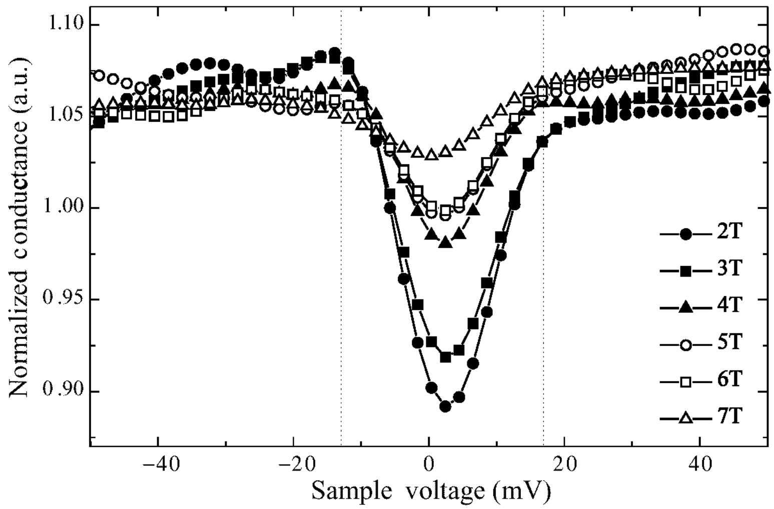

Fig 3. Normalized conductance $(dI/dV)/(I/V)$ curves for the AuFe thin film measured at different magnetic fields. The curves have been obtained by numerical differentiation of the $I(V)$ curves and have been averaged over 25×25 points located within a square area of $20\,\text{nm} \times 20\,\text{nm}$ (see Fig. 2b).

acteristics at 5 K for the area corresponding to the image in Fig. 2b. Fig. 3 shows the normalized conductance curves, $dI/dV/(I/V)$, which have been obtained by numerical differentiation of the $I(V)$ curves. The curves in Fig. 3 have been averaged over 25×25 different points located inside the square of $20\,\text{nm} \times 20\,\text{nm}$. Fig. 3 also demonstrates the influence of a perpendicular magnetic field. The dip near the Fermi level is gradually destroyed when increasing the magnetic field.

Point contact spectroscopy has confirmed that the temperature dependence of the resistivity, $\rho(\mathrm{T})$, is very similar to the voltage dependence of the normalized differential resistance $dV/dI(V/I)$, i.e., the inverse of the normalized differential conductance plotted in Fig. 3, provided the thermal energy is replaced with the voltage across the STM junction [2]. The dip appearing in Fig. 3 below 10 mV reflects the resonant Kondo scattering near the Fermi level. An additional sharp spin-glass maximum, which is expected to appear near $\mathrm{V} \equiv 0$, is absent, probably due to the limited voltage resolution of our STS measurements. The destruction of the Kondo dip in Fig. 3 by a magnetic field is consistent with the destruction of the Kondo effect by a magnetic field as soon as $\mu_B B > k_B T_K$, with μ_B the Bohr magneton. For sufficiently high magnetic fields, the Zeeman splitting of the electron energy levels inhibits the spin-flip scattering processes.

The results in Fig. 3 also reveal an asymmetry in the differential conductance about zero field. When applying a sufficiently large magnetic field, the asymmetry vanishes. A similar asymmetry has recently been observed in point contacts [10] as well as in mesoscopic spin-glass alloys [11]. This asymmetry can be linked to the anomalous thermopower in dilute magnetic alloys [12].

Figure 4 shows normalized conductance curves, $(dI/dV)/(I/V)$, for 3 different positions on the surface of the AuFe film at magnetic fields of 2 T and 5 T, respectively. Again, the curves have been obtained by numerical differentiation and have been averaged over 25×25 points within a square of $20\,\text{nm} \times 20\,\text{nm}$. Although the Kondo

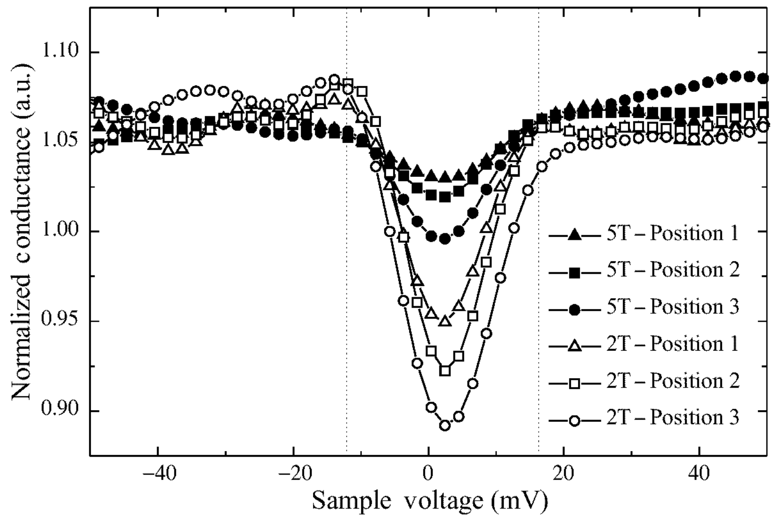

Fig 4. Normalized conductance $(dI/dV)/(I/V)$ curves for 3 different positions on the AuFe film at magnetic fields of 2 T and 5 T, respectively. The curves have been obtained by numerical differentiation of the $I(V)$ curves and have been averaged over 25×25 points located within a square of $20\,\mathrm{nm} \times 20\,\mathrm{nm}$.

dip is consistently destroyed by a magnetic field, the amplitude of the dip apparently depends on the position. More detailed experiments are needed to establish a closer link between the amplitude of the Kondo dip and the local film morphology (local film thickness) On the other hand, systematic measurements as a function of the AuFe film thickness may allow to clearly identify intrinsic size effects.

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